AN INVESTIGATION OF VARIOUS TYPES OF ELECTRICAL DISTRIBUTION SYSTEMS FOR WARSHIPS

BY

RICHARD VERNON SMITH

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May 19, 1950

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Naval Engineer, a thesis entitled "An Investigation of Various Types of Electrical Distribution Systems for Warships" is herewith submitted.

Respectfully,

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I. Summary

The radial system of electric power distribution currently used in warships has proved highly reliable. However a discontinuity of power is introduced whenever a load is shifted from one source of power to another. This usually occurs in after battle damage when a discontinuity of fire power and other vital services can least be supported.

This thesis considers two possible substitutes for the radial, split-plant system; distribution by a network; distribution by a radial system in which the alternate feeders to the loads most requiring continuity are tied to a common bus at the load. In the latter plan, inverse power relays are provided at either end of the feeders to retain the load control feature of the radial system (the ability to disconnect any load from any switchboard by a circuit breaker at the board.)

To determine the features of a network system to be expected in a shipboard application, the network analyzer was used to make an actual layout. Normal operation, damaged operation and short circuit conditions were all studied. The best arrangement of generator feeders was investigated under all of these conditions. The findings are summerized in the paragraphs that follow.

The current loading of cable in a network is aided by delivering power to various parts of the network in proportion

to the power needs of that part. This goal is facilitated when generators can be placed in areas where the heaviest loads exist. Division of power among the various feeders emanating from a generator must also be proper to attain this objective. Increasing the impedance of feeders carrying excess current by means of a reactor was found to be better than decreasing the impedance of feeders carrying a deficiency of current.

Selective operation of limiters in a network, even after damage, requires at least two feeders from different generators to each end of the network. Reactors, which aid in arranging cable loading, also aid in current distribution under short circuit.

Load control is difficult to arrange in a network system. The need for load control can be avoided if the generators are large enough relative to the total load.

Continuity can be attained in a radial system for the loads most requiring it by tying their feeders to a bus at the load and providing inverse power relays on these feeders.

The best method, presently feasible, of obtaining improved continuity of power is to connect the load and its feeders to a common bus at the load and to provide inverse power relays at either end of the feeders.

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II Introduction

Although the distribution of electric power in warships has been perfected to a high degree of reliability, the matter of continuity of power has not been so readily dealt with. For this reason both the British and the Americans have given serious consideration or actual trial to systems other than the radial, split-plant system now standardized in our warships. The hope has never died that one of these schemes of power distribution could be perfected to the point of equal reliability and improved continuity as compared with radial distribution.

Standard practice in the American Navy requires two or three separate cables for each vital load and one cable for each non-vital load center. Each of these cables comes to a given load center from a different generator and serves as an alternate source of power. The result is that the many feeders required run in large groups through fore and aft cableways while alternate paths are kept independant by running the various feeders to any one load in different cableways, physically remote from each other. Since no two generators may be run in parallel, a selective device must be placed at the load which will automatically or manually shift from a cable on which power has failed to another which may yet be intact. This introduces a discontinuity, usually under battle conditions when it can least well be supported. The problem is therefore to provide in some acceptable manner

parallel sources of power at each load. In that way the loss of one source will not interrupt the power to vital equipment.

Both American and British experience with parallel operation of generators has been blightted with maloperation of protective devices. It can be expected, nevertheless, that this objection will be short lived. Especial hope is offered with the prospects of adapting the current limiter (high capacity fuse) to Naval use. Commercial power companies have long used current limiters throughout their networks with singular success. The simplicity of fuse construction precludes improper operation, and experience has born out this conclusion. It is therefore quite understandable that the Navy Department has kept up its interest in the possibility of parallel operation or power sources, even in the face of previous discouraging results.

The system of power distribution most frequently proposed as a substitute for the present radial, split-plant system is the network system. Networks have been the standard method of power distribution ashore for many years and have proved fully reliable. In order to evaluate the possibilities of such a system, the network analyser was employed to study the problems peculiar to shipboard. It is the results of this study which are presented here in this thesis.

The idea of using networks on ships is not a new one, and several sound conclusions have already been reached. It is generally agreed by those who have studied the problem that there is a definite improvement of continuity over that of the radial system. It has also been found that more weight is required. In smaller ships it was felt that the emergency generators were too small to be tied in to the network so that a separate distribution system for these generators would be required. The systems described in this paper were specifically designed to minimize the first of these objections and to eliminate the second.

Several axioms for shipboard networks have been passed down from previous studies and were accepted as definite criteria. All of these are aimed at providing selectivity in the case of short circuit. It will shortly be seen that this requires that all limiters in the network be of the same size (except those to the loads and sources) which in turn requires that all cable be of the same size. This was taken the first axiom.

If a fault occurs in the middle of a cable, the limiters at either end of the cable leading to the junction should open. In order that the proper limiter burn out before any other, it is considered necessary that its current be at least one and a half times larger than that of any other. To obtain this objective it has been found necessary to provide at least four cables at each junction. This means

that while fault current is flowing out of the junction into the damaged cable, it is flowing into the junction through at least three other lines. This division of current generally results in at least one and a half times as much amperage in the faulted line, thus providing selective operation of the fuses. The same results may be obtained when there are only three cables at a junction, but a rather small inequality in the division of current between the two which are feeding into the junction will result in the larger being too near in magnitude to that of the faulted cable.

Previous practice has always been not to require that diesel generators be suitable for paralleling with the turbogenerators or with each other. To make paralleling possible, suitable damping windings and possibly a flywheel must be added. However when it is considered that the entire emergency distribution system can be eliminated, the extra cost and weight are more acceptable.

Another less obvious difficulty arises when several generators are tied in to the same network. As long as operation is normal, the load may be divided among generators in proportion to their size; but damage may remove some of the generators from service, leaving too large a load for the remaining units. In the case studied in this thesis, each main generator is large enough to carry the entire load of the ship. The emergency diesel generators, however, are each

capable of carrying only one quarter this amount. In the radial system, it is possible to limit the number of loads carried by any generator and to select among the various connected loads simply by open-circuiting the feeders to undesired loads. Obviously some such control of loading must be used to permit the diesel generators to feed into the network.

Several methods of paralleling generators are possible which do not give up control over the number of loads which must be fed. The simplest is to use bus ties between the generator boards and employ radial distribution. However this improves continuity only in the case of a generator failure. The load still must be shifted from one radial feeder to another whenever power fails on the feeder in use.

The second method would parallel the generators at the loads instead of at the switchboards. This requires radial distribution and the various cables to any given load are tied together in a junction at the load. In order to disconnect any load from the system, each of the radial feeders to it must be opened at each of the individual boards. To make it possible to control the loading of a generator from its own board alone, inverse power relays would have to be placed on the feeders whenever more than one is run to a single load. If this were not done, power could flow out any feeder in use to a load junction, thence to other boards and to any load these other boards might be feeding. Inverse power relays would prevent power flow in the inverse direction

(toward the generator) in the various feeders and would in that way make only one path available from a given generator to a given load. This path could then be opened or closed at the switchboard of the generator in question giving complete control locally of the loads to be supplied. The objection to this is the large number of relays required and the consequences of a sticky relay.

A third plan to control the loading of a generator would provide relays on non-vital loads which would operate when a high frequency signal was injected into the distribution system. This would not necessarily be intricately designed to give individual control over each non-vital load but would at least permit unloading the excess power requirements in time of need. This plan has much to commend it: false signals are rather easily prevented and a sticking relay will not defeat the system. Furthermore it is equally applicable to radial and to network distribution.

With network distribution, the choice of methods for load control is somewhat more limited. A network may be made divisible into sections which can be dropped from the system or fed independently of other sections. An emergency distribution system of radial type may second the network. In the work which follows, a combination of both was used.

III Procedure

The attack followed by this thesis may be divided into three parts: laying out a suitable network for study, setting up the network on the network analyzer, and refining the layout in accordance with the information obtained from the analyzer. This section of the thesis will follow through the details of these steps.

Because of the limits imposed by time and the size of the analyzer, it was necessary to design for a fairly small ship. To keep the design practical it was decided to design for a ship already in existence. Complete information on the electrical system on the 692 class destroyers was available, making this a natural choice. Before long it was discovered that even for this limited design all but a few elements on the analyzer were required to make the network. The conclusions, however, are applicable to shipboard networks of any size.

The geometry of a ship gives a characteristic shape to its electrical distribution system. Long fore-and-aft runs of cable with short runs in other directions are naturally to be expected. The first decision was therefore the number of longitudinal cables to use. This can not usefully be more than the number of locations in the cross-section which can be considered sufficiently remote from each other so to prevent damage to more than one location from a single hit. The number of such locations was judged to be three on a

destroyer. Previous studies of destroyer network systems have used four longitudinal runs without increase in weight over three, but it was felt that a study involving only three fore-and-aft members was the most suitable for the size of the analyzer. No lack of generality in the conclusions resulted from this. The locations chosen for the longitudinal cable are shown in Figure 1.

The next detail to be fixed was the number and location of the athwartship cables. In order to provide multiple paths to vital equipment, it is necessary to have a node in the network located at the equipment. The nodes are made by connecting each of the three longitudinal runs of cable to each other in the athwartship plane. This follows the axiom that at least four fuses (other than load fuses) must be found at each node. The number of places at which athwartship ties were made (appearing as triangles in Figure 1) was determined solely by the number of vital loads to be supplied.

The next step was to enter the cable lengths and wattages required by the system. Load sizes were taken from the operating loads given in Bureau of Ships plan number DD692-S6202-301 Alt. 3 entitled Preliminary Power Analysis. Cable lengths were estimated from the geometry of the ship. The vertical, horizontal and athwartship distances between the ends of the cable were added plus an allowance of ten feet which might be required at the ends; this sum was then

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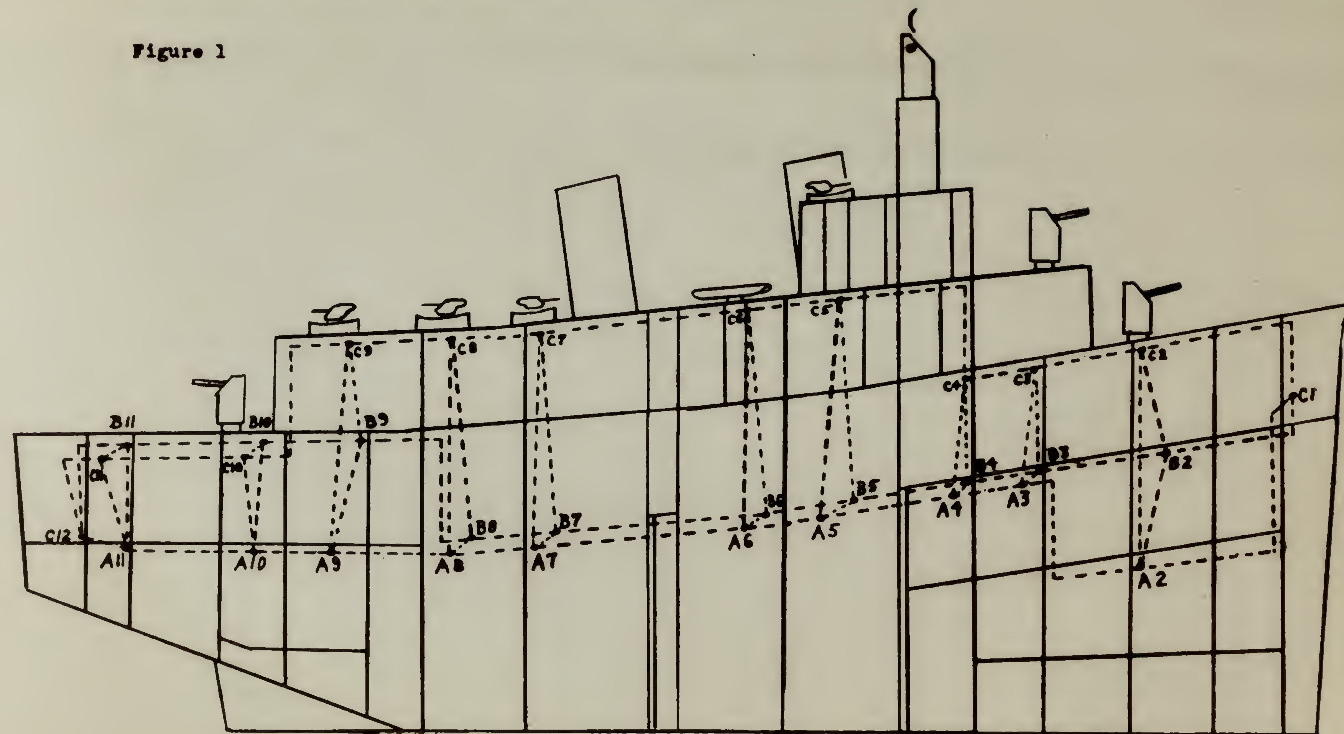
Network for 692 Class Destroyer

Diagramatic Elevation of Network without Feeders

Figure 1



increased by ten percent to allow for slack and obstructions. Both the calculated lengths and the power requirements are displayed in Figure 2.

The cable size necessary was estimated as THFA 250 with a larger for the generator feeders. Impedances were then easily found and the analyzer was set up in a routine manner. Generator feeders were not included at first as their exact location was to be investigated with the analyzer. The bases chosen for a per unit representation of the designed system and the board analogue were as follows:

	System base	Board Base	Ratio, System to Board
Voltage	450 v.	125 v.	3.6 to 1
Current	2800 a.	1 a.	2800 to 1
Impedance	.16 ohms	125 ohms	1 to 780
Vector power	1250 KVA	125 VA	10 to 1

Transient reactance, when required, was taken as .17 per unit. The power factors of individual loads was not available so an average power factor for inductive loads was calculated by assuming an overall power factor of .80 and unity power factor for heating and lighting loads. This gave an average value of .73 for inductive loads.

Three generation plans were tried as the investigation proceeded. In Generation Plan #1 each main generator was given two feeders to local points and one to a remote point; in Generation Plan #2 each main generator was given feeders to one local point and two remote points; Generation Plan #3

Network for 692 Class Destroyer

Operating Loads and Cable Lengths

Main Feeders not Shown

Cable lengths given in feet

Figure 2

differed from Generation Plan #2 by the addition of a reactor in the heaviest loaded feeder of each main generator.

In all three generation plans the two diesel generators were fed into the forward diesel generator switchboard and the after diesel generator board was eliminated. This arrangement followed after some preliminary studies which showed that the forward diesel generator would be overloaded and the after one underloaded. Placing both of these generators forward put them in the area of greatest electrical load which was a definite advantage.

Distribution from the forward diesel generator switchboard was accomplished by four feeders joining the network at points of vital loading (Mount 51, Mount 52, I.C. Room, Radio-Radar.) By a simple arrangement it is then possible to have a breaker which will disconnect both the feeder and the vital load from the network leaving the feeder and the load connected to each other. However these breakers would render standby service only. Their operation may be manual or automatic on inverse power flow.

The normal method of protecting the diesel generators would be by means of inverse power relays which would segregate the forward part of the network from the after part. There relays would be located two between nodes A5 and A6, well separated physically, two similarly between nodes B5 and B6, and two between nodes C5 and C6. With this series-parallel combination the failure of any one relay to open or

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shut would not interrupt the correct operation of the system as a whole. The most vital loads on the ship are fed from this forward section of the network, the important exceptions being the steering gear and the after 5" mount. If the ship is reduced to such a state of emergency that both main generators are out of commission, steering may well be done by hand power if required at all. However sufficient capacity remains in the diesel generators to run a feeder direct to the steering gear. Such a feeder would not tie in to the network but would permit switching the steering gear panel from the network to the emergency feeder. As for the after 5" mount, it should be noted that the capacity of the diesel generators is only sufficient to carry two of the main mounts. The present arrangement actually in use permits selection of either Mount 51 or Mount 52; the system considered in this thesis could also provide selection between Mount 53 and Mount 52 with the feeder to Mount 53 arranged similarly to that proposed for the steering gear. In any case these emergency feeders would not effect the operation of the network and were not included in any of the work done on the analyzer.

When the method of generation had been selected for a run and properly introduced into the analyzer set-up, it was then necessary to establish the boundary conditions. In each case not involving short circuits, one main generator was held slack on active power and at the rated voltage of

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the system (125 volts on the analyzer corresponding to 450 volts in the actual system.) The active and reactive power on the other generators were so set as to divide them among the generators in proportion to their ratings. The generators were assumed to be of the same size as those in use in the 692 class destroyer, namely:

Turbo-generators 400 KW each

Diesel generators 100 KW each

Each generator is capable of supporting a 25% overload for two hours and a 50% overload for five minutes.

Runs simulating short-circuit conditions were made by replacing each generator by its transient impedance. Using a method of superposition, voltage was impressed on the system at the location of the short-circuit. The resultant currents flow in the reverse direction of the actual currents under short circuit but nearly equal them in magnitude. The exact short circuit currents may be obtained by superimposing the vector values obtained by the above short circuit method upon the vector currents without short circuit. The latter are small compared to the short-circuit currents so that the values obtained by the approximate method just described may be taken as correct.

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IV Results

After some preliminary trials on the network analyzer, Generation Plan #1 was chosen for the first complete analysis of the network. The results are presented in Figure 3. The points of heaviest current flow are seen to be the fore-and-aft lines just forward of the forward generator (A5 to A6, B5 to B6, C5 to C6) and just aft of the after generator (A8 to A9, B8 to B9, C8 to C9.) Also heavily loaded are the athwartship cables at each main generator (A6 to B6, B6 to C6, C6 to A6, similarly triangle 8.)

Damage to any of the athwartship cables still leaves a large number of other such cables over which the current flow can distribute itself; damage to any longitudinal cable sharply reduces the number of available cables to maintain the current flow in the fore-and-aft direction. The analyzer showed that with two cables damaged the current in the third would be:

In use	Open	Current
A5 to A6	B5 to B6, C5 to C6	126 amps
B5 to B6	C5 to C6, A5 to A6	154 amps
C5 to C6	A5 to A6, B5 to B6	132 amps

The effect of damage to the diesel generators was next studied. Figure 4 presents the current flow when these generators are not operating and each main generator carries half of the total load. Again consideration was made of damaged longitudinal runs of cable with the following results:


Network for 692 Class Destroyer
Generation Plan #1
Normal Battle Operation
THFA 250 in Network
THFA 400 in Feeders
All currents given in amperes
Vector Power:
DG 1 6.0 - j4.6 KVA
DG 2 6.0 - j4.6
TG 1 23.3 -j19.7
TG 2 23.2 -j17.0
T.G. 1
T.G. 2
D.G. 1
D.G. 2
12
11
10
9
8
7
6
5
4
3
2
1
B
C
A
D
E

Figure 5

Network for 692 Class Destroyer

Generation Plan #1

Turbo-generators only

THFA250 in Network

THFA 400 in Feeders

Currents shown in amperes

Vector Power:

TG 1 29.3 - j22.9 KVA

TG 2 29.3 - j22.9

Figure 4

A5 to A6	B5 to B6	C5 to C6
open	171 amps	129 amps
140 amps	open	143
123	168	open
194	open	open
open	221	open
open	open	196

A8 to A9	B8 to B9	C8 to C9	TG2 to C12
105 amps	open	open	157 amps
open	92½ amps	open	179
open	open	134 amps	134

The final study made on Generation Plan #1 was to consider the operation of one turbo-generator only. Figure 5 shows the currents resulting from the operation of Turbo-generator #1. The cables loadings are found to be so great as to approach closely the cable capacity in several places. In these cases any damage to parallel lines would throw an overload on the lines now so close to their limit.

The current distributions obtained in figures three to five show clearly that insufficient power is being fed into the ends of the network. The result is that the cables near the center are loaded to capacity while those at the end are carrying only a fraction of their maximum. When the lines feeding to the ends of the network were each

Network for 692 Class Destroyer

Generation Plan # 1

Turbo-generator #1 only

THFA 250 in Network

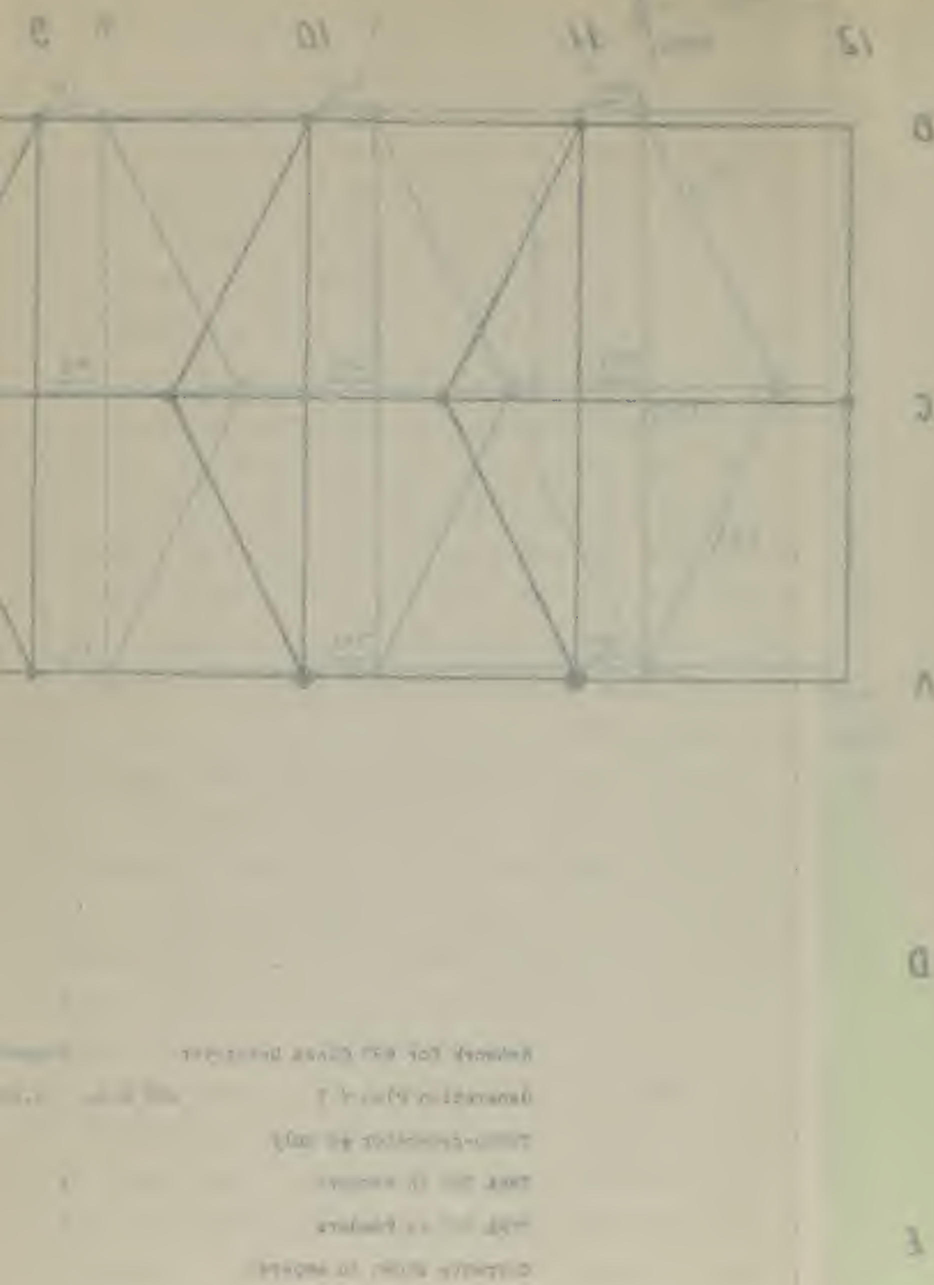
THFA 400 in Feeders

Currents shown in amperes

Vector Power:

TG 1   58.8 - j45.6 KVA

Figure 5



paralleled by another of the same size, no significant improvement was found. It was also found that the feeder from TG#1 to A6 and the feeder from TG#2 to B8 were of no importance to the current distribution. Short circuit studies indicated the same need for feeder rearrangement.

With the above facts in mind, a new generation plan was tried which proved to be unsuccessful in selective operation under short circuit. This plan is presented in Figure 6. Although the lines to the shorted node carry in each case the greatest current, it is not one and a half times greater than the currents in other lines. The result would be the opening of the limiters shown on Figure 6 (A8 to A9, B8 to B9, C8 to C9, B9 to C9, C9 to C10.) This would sever the after end of the network off; still further modification was needed.

In another attempt to divide the currents more equally among the generator feeders, reactors were introduced in the lines TG#1 to B6 and TG#2 to A8. The results are shown in Figures 7, 8 and 9. In Figure 7 the main generator feeder containing the reactor continues to carry the largest part of the current but most of this goes to the large engine room loads at B6 and A8. The longitudinal lines are carrying somewhat less current in the central parts of the network. The improvement made by this arrangement is most pronounced in the short circuit runs presented in Figure 8 and Figure 9. Here the network is effectively selective, and only the lines leading into the shorted node will be opened at the limiters shown in the figures.

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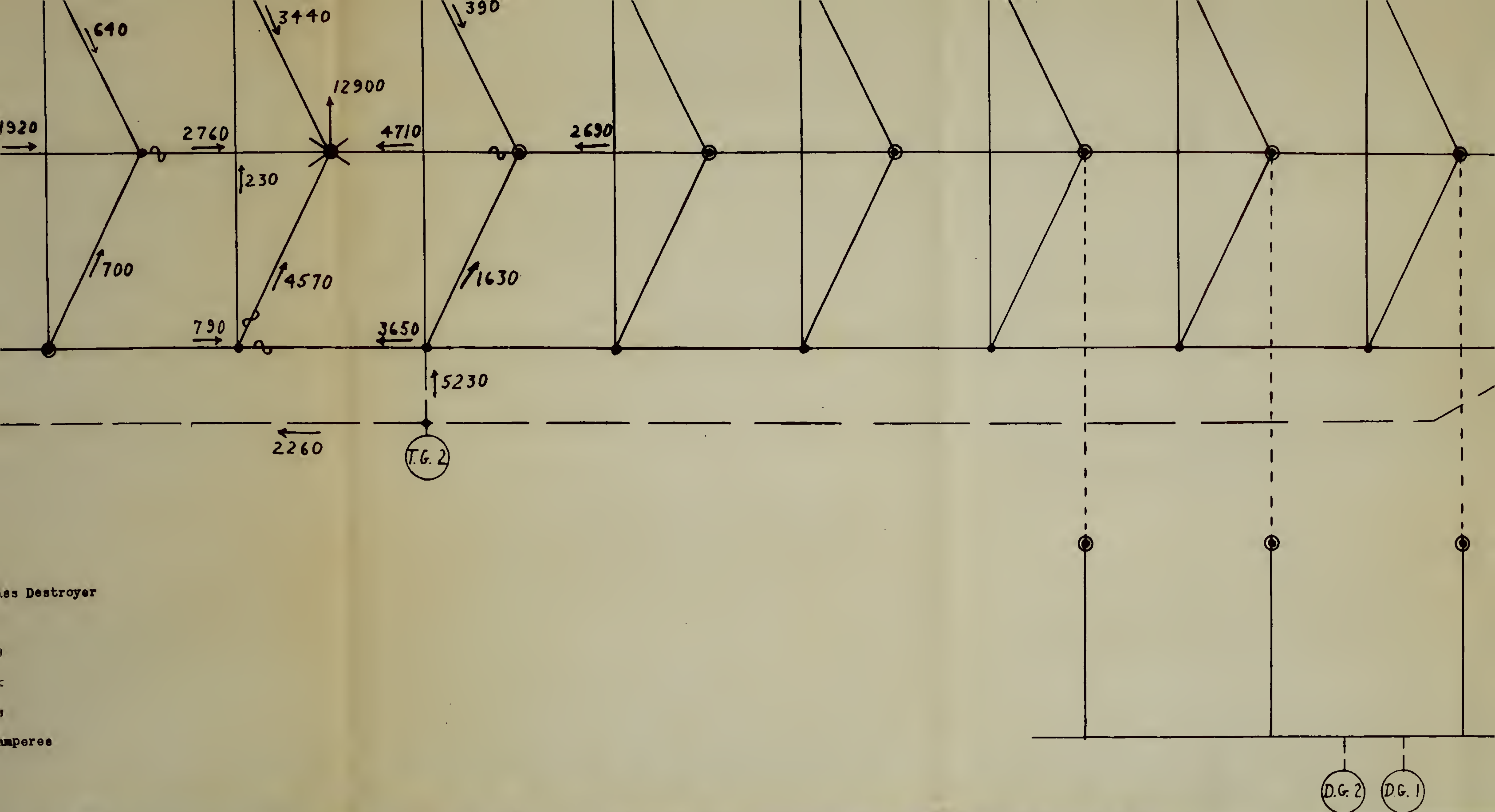

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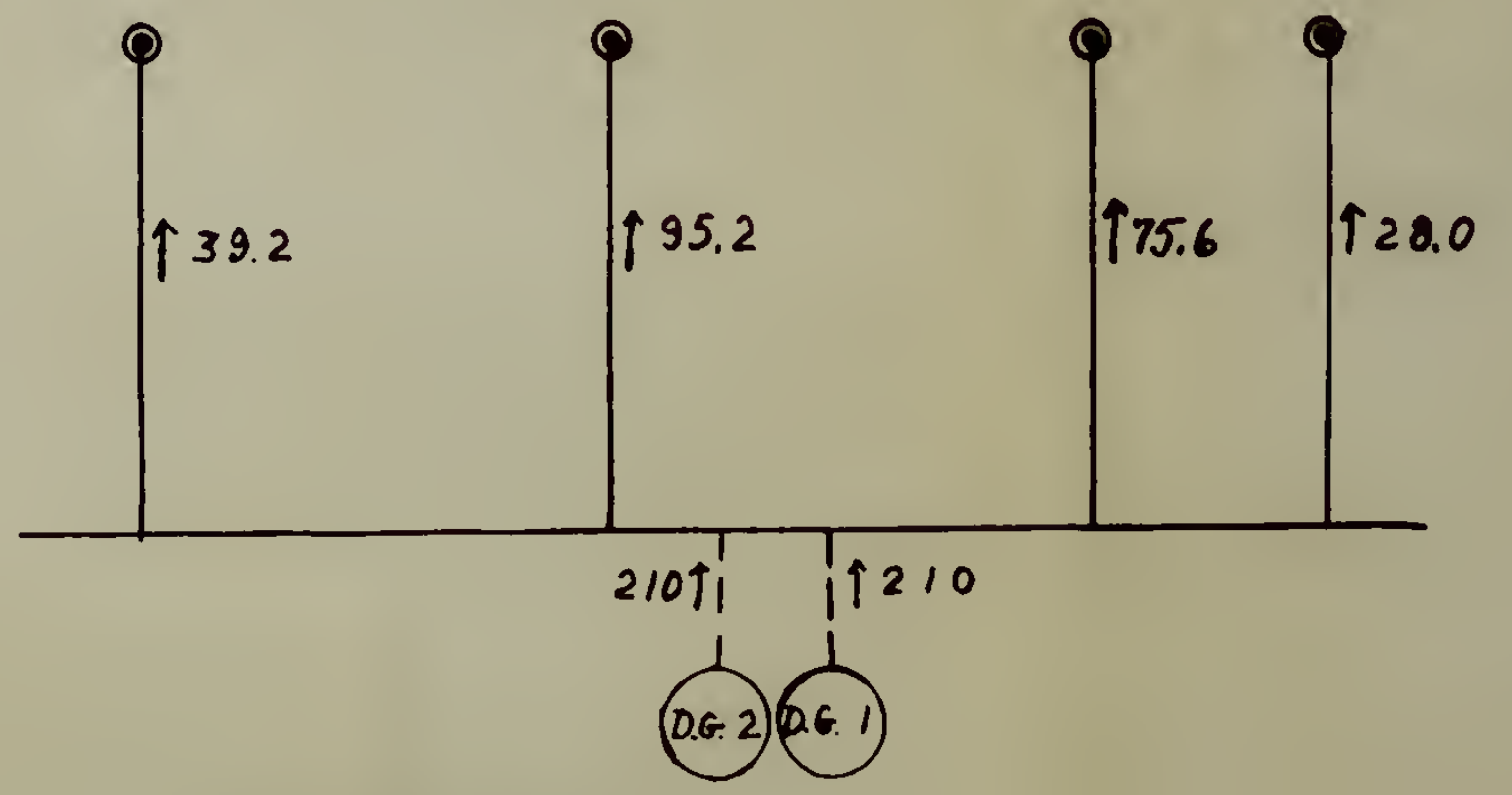
Figure 6



D

E

Network for 692 Class Destroyer

Generation Plan #3

Normal Battle Operation

THFA 250 in Network

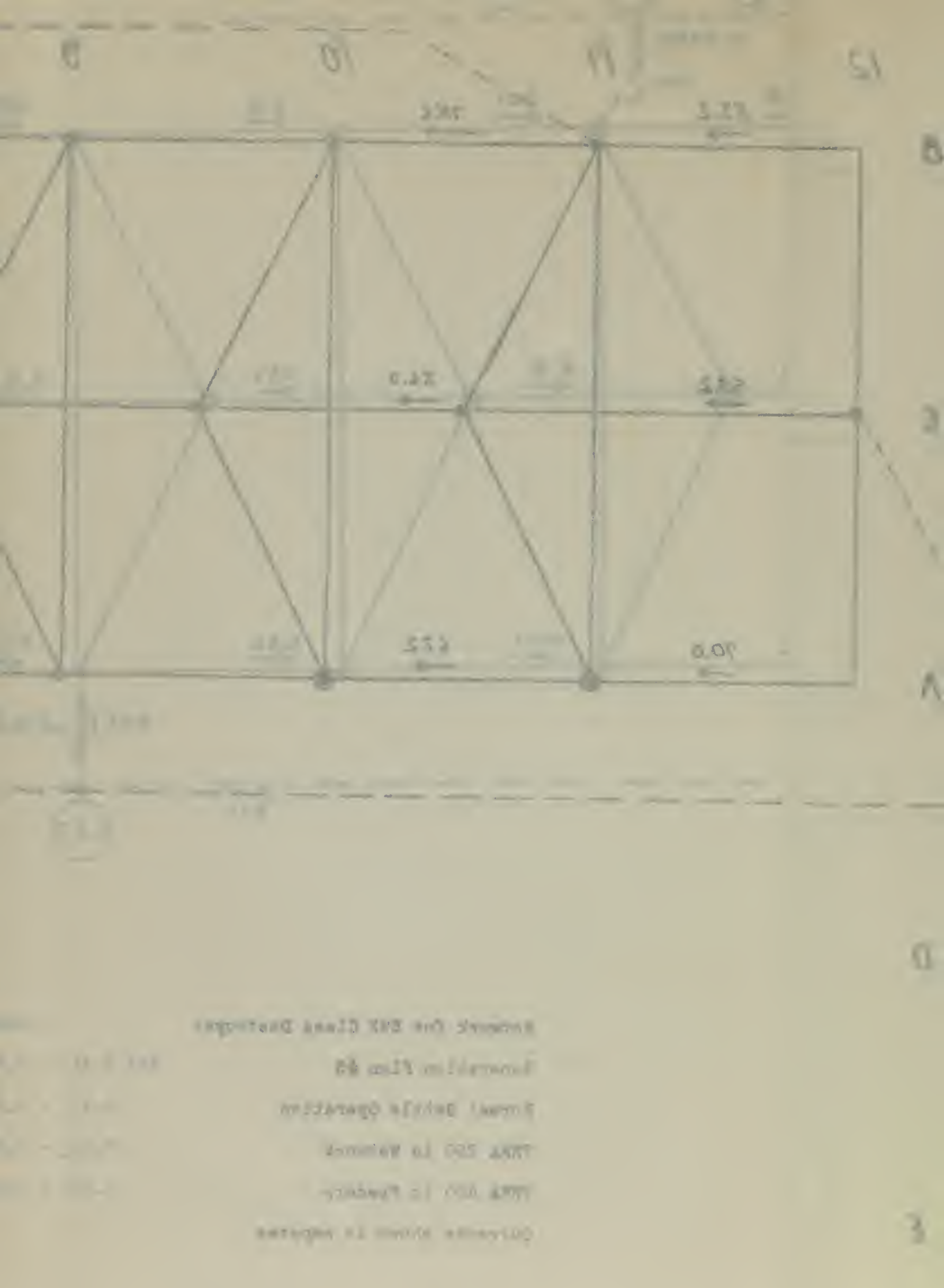
THFA 400 in Feedere

Currents shown in amperes

Vector power:

DG 1	6.4 - j4.4	KVA
DG 2	6.4 - j4.4	
TG 1	23.8 - j18.6	
TG 2	21.8 - j18.1	

Figure 7



Network for 692 Class Destroyer

Generation Plan #3

Short Circuit at C3

THFA 250 in Network

THFA 400 in Feeders

Currents shown in amperes

Figure 8

Network for 692 Class Destroyer

Generation Plan #3

Short Circuit at C9

THFA 250 in Network

THFA 400 in Feeders

Currents shown in amperes

Figure 9

V Discussion of Results

The most noticeable feature of the network is the variation in current loading among the different cables. The more evenly this division can be made among lines performing parallel functions, the smaller the required cable size may be. Some correction may be made within the network itself. Larger ships should always have at least four longitudinal cable runs instead of three. The larger number permits smaller size and the increase in weight in the system (if any) will be negligible. On the other hand the larger number of cables will withstand damage better if the ship is large enough to locate each run where it will not be in the same damage area as another such run. Destroyers represent the borderline case. For the 692 class, the design would be improved by using four lines amidships (Mount 52 to Mount 44 inclusive) with three lines in the finer portions. The arrangement of feeders used from the diesel generators makes an effective substitute for the fourth line in that area.

Cable loading can be reduced if the power is fed into the network at the place and in the quantity locally required. If the power is not apportioned to the local need, there must be current flow away from the area. This would seem to call for locating the generators in the areas of greatest power consumption, except for the fact that location of the turbo-generators is fairly well fixed in Naval vessels by

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the position the engine rooms in the midship section of the ship. As in Figures 3 and 7, this results in light power flow in the sections between the generators with heavy flow toward the ends of the ship. However the location of the diesel generators is more freely selected and they should be placed where they can supply the heavy-load areas with the least current flow.

Whether or not the location of the generators is favorable, feeders carry the power to remote as well as local parts of the network. However because of the greater distances to the further points, current flow is heavier in the shorter feeders. Control of the division of power among the feeders is necessary to equalize the cable loading in the network. Experimentation with the network analyzer showed that it is more effective to increase the impedance of the short feeders than to lower the impedance of the long ones. Lowering impedance means using a parallel cable to a line which is already of very large size. Increasing impedance can be done simply by the use of additional resistance with a loss of about half a kilowatt per generator dissipated as heat. A reactor for high current flow is more cumbersome but would avoid most of the power loss. The optimum size of reactor was not investigated; a variable reactor might even be considered.

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happen, or the current approaching from one end is insufficent, selective operation of the limiters will not take place. Figure 6 is an example of this. Here again the use of a reactor cured the difficulty as shown in Figure 9. Generation Plan #2 (and subsequently #3) was formed when it was realized that it was necessary for damage control reasons to provide more than one feeder to the ends of the network. Otherwise damage to a single feeder could greatly impair the resistance of the network to short circuit.

Load control, which is the prominent feature of the radial system, is entirely absent in the network system. Because the vital load of the 692 class destroyer is located in the forward end of the ship and because of the size of the generators in this class of ship, the problem was simplified. Each main generator could carry the total load of the ship so that load control was not required for them. By placing the diesel generators together in the heavy load area forward and by making it possible to disconnect this part of the network from the rest, the diesels were protected from overload in case of failure of the two main generators. However on larger ships no one generator can carry the whole load of the network. The best arrangement is to have:

2 or 3 generators each capable of carrying all the load

4 or 5 generators each capable of carrying half the load

6 or 7 generators each capable of carrying 1/3 the load

When damage reduces the number of generators below that needed

to supply the network, the damage will be so severe that casualty power will probably suffice. Other means of reducing the load have been discussed previously, but all have the drawback of reducing the simplicity of the network.

Increased continuity of power remains the undisputed virtue of the network. However the same continuity plus load control can be had for the radial system loads most requiring it by joining the normal, alternate and emergency feeders to a common bus with the load and near it. By placing inverse power relays at each end of the feeders, load control is retained as well as protection in the case of false operation of one of the relays. The number of loads provided with this "continuous power bus" would necessarily be limited to keep down the number of inverse power relays, and the excess weight probably would not exceed that required for a network system.

The reliability of a network should equal or exceed that of the radial distribution providing its cables are of such capacity that they will not be overloaded when parallel cables are damaged. The network system will weigh more than the radial system so there will be a temptation to design network cables for some condition of loading less severe than the worst possible. Use of inverse power relays may also reduce the reliability of the system if they are not carefully engineered. The use of series-parallel combinations of relays, which has been suggested throughout this thesis, should minimize any ill effects of maloperation.

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VI Conclusions

Cable loading in a network is aided by delivering power to various parts of the network in proportion to the power needs of that part. This goal is facilitated when generators can be placed in areas where the heaviest loads exist. Division of power among the various feeders emanating from a generator must also be proper to attain this objective. Increasing the impedance of feeders carrying excess current by means of a reactor was found to be better than decreasing the impedance of feeders carrying a deficinecy of current.

Selective operation of limiters in a network, even after damage, requires at least two feeders from different generators to each end of the network. Reactors, which aid in arranging cable loading, also aid in current distribution under short circuit.

Load control is difficult to arrange in a network system. The need for load control can be avoided if the generators are large enough relative to the total load.

Continuity can be attained in a radial system for the loads most requiring it by tying their feeders to a bus at the load and providing inverse power relays on these feeders.

VII Recommendations

The best method, presently feasible, of obtaining improved continuity of power is to connect the load and its feeders to a common bus at the load and to provide inverse power relays at either end of the feeders. This system should be tried in an actual installation.

Study should be continued on network systems as a possibility for future use.

VIII Appendix

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